Fractional flow reserve (FFR) is widely used in clinical practice to assess severity of functional coronary artery stenosis; it is the ratio of distal intracoronary pressure (Pd) to aortic pressure (Pa) measured during pharmacologically induced hyperemia. FFR has been shown to be effective at reducing the rate of stent implantation and improving cardiac outcomes compared with angiographic guidance alone, and its use is supported by international guidelines.1,2 Large clinical studies such as Fractional Flow Reserve versus Angiography for Multivessel Evaluation (FAME) used conditions of maximal hyperemia achieved by central-line administration of intravenous adenosine to estimate FFR.3–5 Other landmark studies such as DEFER used both intravenous and intracoronary adenosine, although the frequency of the mode of adenosine administration was not reported.3 Intravenous adenosine administration is thought to provide the most stable conditions of hyperemia for measurement of FFR. However, even in the best hands, it is possible that intravenous adenosine results in variable changes in systemic blood pressure, which can lead to alterations in FFR lesion classification. Attention is required to ensure FFR is measured under conditions of stable hyperemia, although the FFR value at this point may be numerically higher. (Circ Cardiovasc Interv. 2013;6:654-661.)

Key Words: adenosine ■ angiography ■ blood pressure ■ coronary disease ■ fractional flow reserve, myocardial ■ hemodynamics

Editorial see p 602

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WHAT IS KNOWN

• Fractional flow reserve (FFR) has been shown to be effective at reducing the rate of stent implantation and improving cardiac outcomes compared with angiographic guidance alone.
• Clinical trial data are almost exclusively based on FFR values measured during maximal steady-state hyperemia induced by intravenous adenosine infusion.

WHAT THE STUDY ADDS

• Intravenous adenosine results in variable and unpredictable changes in systemic blood pressure.
• Measuring FFR prior to attainment of maximal steady-state hyperemia can lead to changes in clinical decision making.
• FFR during maximal steady-state hyperemia may be numerically higher than at other times during measurement.
• Using intravenous adenosine, on average it takes ≥60 seconds to achieve stable pressure conditions suitable for measurement of FFR.
• The heterogeneous hyperemic response of adenosine compounds suggests that new agents with vastly different pharmacological profiles (such as regadenoson) will need further evaluation in clinical outcome trials prior to adoption into routine clinical practice.

important changes in categorization can inadvertently occur when FFR values lie close to the treatment threshold (ie, ≤0.8 or <0.75) because of small changes in the response to adenosine administration, possibly related to variations in peripheral and central hemodynamic responses. Such changes can frequently be observed when the initial Pd/Pa ratio is lower during the first moments of adenosine administration than during stable hyperemia (Figure 1). Not only may initial FFR values be lower than those attained during stable hyperemia, but they also tend to be more variable, and it is difficult to interpret their meaning in the context of rigorously performed FFR clinical outcome studies, which use the FFR values taken at maximal stable hyperemia as the reference standard.

FFR should be measured under steady-state hyperemia. However, in clinical practice, the time at which stable hyperemia is achieved can sometimes be difficult to determine, and often the lowest rather than stable FFR value is used for clinical decision making. This is especially apparent when relying on automated FFR consoles, which seek the lowest recorded Pd/Pa ratio rather than seeking the ratio at stable hyperemia. With this in mind, our study aimed to evaluate the hemodynamic response to intravenous adenosine. Specifically, we aimed to evaluate the frequency by which changes in Pd/Pa lead to changes in clinical categorization when FFR measurements are obtained during peak and stable hyperemia and the extent to which central hemodynamic changes influence coronary Pa and Pd, and the Pd/Pa.

Methods

Study Design
This nonrandomized retrospective analysis included coronary catheter data from 283 unsel ected consecutive patients (310 coronary stenoses) who underwent coronary angiography with FFR measured using intravenous adenosine as part of clinical management at 3 sites (Imperial College Healthcare, London, United Kingdom; Cardiovascular Institute, Hospital Clinico San Carlos, Madrid, Spain; St. Thomas’ Hospital, London, United Kingdom). Cases where intracoronary adenosine was used to measure FFR were not included in the study. Patient demographics are reported in Table 1. All subjects gave written informed consent in accordance with the protocol approved by the local ethics committee prior to undergoing coronary angiography.

Procedure and Data Acquisition
Coronary catheter data were obtained in the standard way, using a 0.014-inch pressure sensor–tipped wire (PrimeWire, Volcano Corporation, or Radi PressureWire, St Jude Medical, Minneapolis, MN) passed into the target vessel via a guiding catheter during diagnostic angiography. Pressure recordings were made at baseline and throughout intravenous infusion of adenosine at a rate of 140 µg/kg per minute administered via a femoral venous sheath, and hemodynamic data were stored on the Combowmap and Radi analyzer.

Reservoir Pressure: A Measure of Systemic Vascular Resistance
Reservoir pressure (Pr) is the pressure generated during systole when more blood is ejected from the heart than can move out to the peripheral vessel. During this phase, the aorta distends under pressure (Pr) to accommodate the additional systolic blood volume. Later during diastole, Pr declines as aortic distension recovers providing perfusion to the vasculature. In this way, the reservoir integrates the on–off ejection of the heart into a continuous blood flow throughout the entire cardiac cycle, and as such, Pr is a composite of compliance of the large elastic arteries (predominately the proximal aorta) and a measure of peripheral vascular resistance (or outflow to blood). Pr was calculated using the standard reservoir-wave separation as described previously. By measuring how Pr changes, it is possible to assess the extent to which vasodilators, such as adenosine, act to reduce coronary perfusion from the aorta via peripheral vasodilatation.

Analysis of Hemodynamic Data
Data were analyzed using customized software written in Matlab (Mathworks, Inc, Natick, MA). Baseline and stable hyperemia time points were confirmed by visual inspection of each hemodynamic trace, and peak hyperemia was defined as the lowest FFR within 60 seconds of intravenous adenosine infusion and stable hyperemia as when the hyperemic plateau was reached. This analysis yielded mean Pd, Pa, and maximum Pr measurements at baseline, peak, and stable hyperemia after intravenous adenosine infusion.

The lowest FFR during the first 60 seconds (peak FFR) was compared with FFR measured after confirmation of stable FFR. This was designed to reflect a common clinical scenario, often observed when measuring FFR. Automated FFR consoles are designed to track the lowest FFR value. However, it is important that the clinician is able to visually interpret the hemodynamic traces and decide the time when stable hyperemia has been achieved to prevent the potential misinterpretation of an artificially low FFR reading. To avoid this potential pitfall, it is common practice to wait for ≥1 minute after intravenous adenosine before measuring FFR.

Pressure Response and FFR Group Analysis
Data were analyzed to determine mean pressure changes for the entire group in response to intravenous adenosine. Mean time from baseline to stable hyperemia was calculated for the entire group. Mean Δ pressure gradient (Pa-Pd) was also compared. Stenoses were categorized according to direction of mean Pa and Pd change at peak and stable hyperemia, with reference to the previous state. Mean ΔPa, ΔPd, and ΔPr from baseline (expressed in both percentage and mmHg) were
compared between the groups. FFR was calculated using pressure measurements at baseline, peak, and stable hyperemia for all stenoses. Changes in lesion classification between peak and stable hyperemia were analyzed using FFR treatment thresholds of both ≤0.80 and <0.75.

**Statistical Analysis**

Statistical analysis was performed using STATA version 12 (StataCorp LP, College Station, TX). Two-sample t test was used to compare pressure changes at peak and stable hyperemia with those at baseline. The relationship between ΔPa and ΔPd at peak and stable hyperemia was assessed using single-variant regression analysis and F test. To assess clinical characteristics in relation to likelihood of observing a clinical categorization change in FFR between peak and stable hyperemia, first a univariant logistic regression analysis was performed and then variables were put into a multivariant analysis model. Logistic regression analysis was also used to determine the likelihood of observing a clinical categorization change based on pressure response group. For all tests, P<0.05 was considered significant.

**Results**

**Pressure Recordings**

Intravenous adenosine caused a significant decrease in both ΔPa 10.2±10.5 mmHg (−10.0±10.1%) and ΔPd −18.2±10.8 mmHg (−19.8±10.3%), P<0.001 for both (Figure 2). The average time from baseline to stable hyperemia after administration of intravenous adenosine was 68.2±38.5 seconds. ΔPa and ΔPd were closely related under conditions of peak (r=0.75; P<0.001) and stable (r=0.83; P<0.001; Figure 3) hyperemia.

On average, 56% (10.2 mmHg) of the reduction in Pd pressure in response to intravenous adenosine was because of a fall in Pa, and the larger the fall in Pd, the larger the contribution from Pa (Figure 3). For example, when Pd fell by 29 mmHg, the fall in Pa (23 mmHg) accounted for 80% of the entire fall in Pd.

At stable hyperemia, ΔPa ranged from −58.3 mmHg decreased below baseline to 24.3 mmHg increased above baseline. In 19.7% (61/310), Pa was decreased >20 mmHg at stable hyperemia. In contrast, in 14.2% (44/310), Pa was increased above baseline values. The fall in Pa pressure closely followed the reduction in peripheral Pr, with ΔPr at stable hyperemia being −12.4±15.7 mmHg (−10.4±11.9%), P<0.001. ΔPa and ΔPr were closely related under conditions of peak (r=0.9; P<0.001) and stable (r=0.9; P<0.001; Figure 4) hyperemia.

Seven different hemodynamic patterns were observed when stenoses were grouped according to direction of Pa and Pd changes at peak and stable hyperemia (Figure 2). In 62.9% (17/27), hemodynamic patterns changed between different stenoses, within the same patient.
Mean resting Pd/Pa ratio (baseline) for the entire study group was 0.92. With infusion of intravenous adenosine, FFR fell to a nadir of 0.79 (peak), before rising to 0.83 with continued adenosine infusion to achieve stable hyperemia. Overall, the fall in FFR at peak hyperemia reflected a disproportionate fall in Pd, driven mainly by an initial relatively smaller reduction in Pa, leading to an increased pressure gradient and lower Pd/Pa ratio. At stable hyperemia, when ∆Pd more reliably reflects changes in coronary microcirculation, reduction in Pd was less pronounced relative to ∆Pa, leading to a decrease in pressure gradient and an increase in the Pd/Pa ratio. A similar pattern was observed in each of the 7 different hemodynamic groups, with FFR being

<table>
<thead>
<tr>
<th>Group</th>
<th>mean ∆ (mmHg)</th>
<th>Group</th>
<th>mean ∆ (mmHg)</th>
<th>Group</th>
<th>mean ∆ (mmHg)</th>
<th>Group</th>
<th>mean ∆ (mmHg)</th>
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<td>falls below baseline</td>
<td>Pa stable</td>
<td>then rises</td>
<td></td>
<td>Pa peak</td>
<td>falls below baseline</td>
<td>Pa stable</td>
</tr>
<tr>
<td>Pd peak</td>
<td>falls below baseline</td>
<td>Pd stable</td>
<td>then rises</td>
<td></td>
<td>Pd peak</td>
<td>falls below baseline</td>
<td>Pd stable</td>
</tr>
</tbody>
</table>

Figure 2. Changes in aortic pressure (Pa) and distal intracoronary pressure (Pd) at peak and stable hyperemia. Coronary stenoses grouped according to direction of Pa and Pd change at peak and stable hyperemia. This shows 7 different patterns of response. Mean ∆Pa and ∆Pd (mmHg) at baseline, peak, and stable hyperemia are shown for each group and for the total study group.

**FFR Measurements**

Mean resting Pd/Pa ratio (baseline) for the entire study group was 0.92. With infusion of intravenous adenosine, FFR fell to a nadir of 0.79 (peak), before rising to 0.83 with continued adenosine infusion to achieve stable hyperemia. Overall, the fall in FFR at peak hyperemia reflected a disproportionate fall in Pd, driven mainly by an initial relatively smaller reduction in Pa, leading to an increased pressure gradient and lower Pd/Pa ratio. At stable hyperemia, when ∆Pd more reliably reflects changes in coronary microcirculation, reduction in Pd was less pronounced relative to ∆Pa, leading to a decrease in pressure gradient and an increase in the Pd/Pa ratio. A similar pattern was observed in each of the 7 different hemodynamic groups, with FFR being

**Figure 3.** Relationship between change in distal intracoronary pressure (Pd) and aortic pressure (Pa) at peak and stable hyperemia. After administration of adenosine, both Pa and Pd fall. A significant linear relationship between fall in Pd (y axis) and Pa (x axis) after intravenous adenosine infusion was found between both peak and stable hyperemia. The reduction in Pd is attributable in part to a reduction in Pa and in part to vasodilatation of the coronary microcirculation.
lower at peak than during stable hyperemia. However, the degree of change varied significantly between groups (Figure 5).

Lesion Classification

The proportion of cases where the classification changed between peak FFR and stable FFR was calculated for both FFR \( \leq 0.80 \) and FFR <0.75. Pd/Pa ratio was >0.8 for all stenoses at baseline. Using the FFR \( \leq 0.80 \) cutoff, lesion classification changed in 9% (28/310) of cases between measurements made at peak and during stable FFR (Figure 1). When the FFR cutoff of <0.75 was used, the proportion of patients in whom classification changed between measurements made at peak and during stable FFR was 5.2% (16/310). For 0.3% (1/310), FFR crossed the grey zone and was <0.75 at peak and >0.80 at stable hyperemia. Results of regression analysis comparing clinical characteristics in relation to likelihood of classification change in FFR between peak and stable hyperemia are summarized in Table 2. There was no significant difference between the likelihood of observing a change in FFR classification in any of the 7 different pressure responses.

Discussion

This is the largest study to investigate the effect of intravenous adenosine on the pressure recordings used to calculate FFR and the first to link changes in peripheral resistance and compliance with changes in the coronary perfusion pressure and measurement of FFR at different measurement time points. Our results are consistent with pressure changes observed in other studies, which were focused mainly on changes in coronary artery pressure.8–11 The fall in Pd pressure after intravenous adenosine is attributable to a combination of a fall in aortic perfusion pressure, in addition to microcirculatory vasodilatation. Using Pr analysis, a close relationship was found between Pa pressure and changes in large artery compliance and resistance. This study shows how changes in systemic blood pressure (BP) at peak and stable hyperemia may directly alter the FFR value, and how this could lead to differences in lesion classification irrespective of whether either the FFR \( \leq 0.80 \) or <0.75 treatment thresholds are used.

![Graph](image_url)
Hemodynamic Responses to Intravenous Adenosine

After intravenous adenosine infusion, we observed 7 different patterns of Pa and Pd. The pattern of Pr change, as a measure of peripheral resistance and compliance, mirrored Pa in each of the 7 groups, which suggests that the mechanism underlying the hemodynamic response to intravenous adenosine is largely mediated by changes in large artery compliance and resistance. A brief initial rise in systemic BP was often observed in the first moments after adenosine infusion. This may result in a fractional flow reserve (FFR) value that crosses the FFR 0.80 clinical treatment threshold, and which is lower than the FFR value when calculated at stable hyperemia. Similar fluctuations are seen when using the pressure gradient (Pa–Pd) or pressure ratio (Pd/Pa).

Table 2. Logistic Regression Analysis of Clinical Characteristics in Relation to Observed Clinical Categorization Change in FFR Between Peak and Stable Hyperemia

<table>
<thead>
<tr>
<th></th>
<th>≤0.80</th>
<th></th>
<th>≤0.75</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FFR Threshold</td>
<td>Odds Ratio</td>
<td>95% CI</td>
<td>P Value</td>
<td>Odds Ratio</td>
</tr>
<tr>
<td>Age</td>
<td>1.00</td>
<td>0.96–1.04</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td>Sex</td>
<td>0.74</td>
<td>0.30–1.84</td>
<td>0.51</td>
<td>1.68</td>
</tr>
<tr>
<td>Heart rate</td>
<td>0.99</td>
<td>0.95–1.02</td>
<td>0.54</td>
<td>0.97</td>
</tr>
<tr>
<td>% Luminal stenosis</td>
<td>1.00</td>
<td>0.98–1.03</td>
<td>0.76</td>
<td>1.00</td>
</tr>
<tr>
<td>Hypertension</td>
<td>0.72</td>
<td>0.33–1.59</td>
<td>0.42</td>
<td>0.76</td>
</tr>
<tr>
<td>Hyperlipidemia</td>
<td>0.44</td>
<td>0.19–1.00</td>
<td>0.05</td>
<td>1.48</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>1.07</td>
<td>0.47–2.43</td>
<td>0.87</td>
<td>0.13</td>
</tr>
<tr>
<td>Smoking</td>
<td>0.91</td>
<td>0.41–2.03</td>
<td>0.81</td>
<td>1.98</td>
</tr>
<tr>
<td>Chronic renal failure</td>
<td>1.01</td>
<td>0.22–4.59</td>
<td>0.99</td>
<td>0.90</td>
</tr>
<tr>
<td>Previous MI</td>
<td>0.44</td>
<td>0.06–3.39</td>
<td>0.43</td>
<td>1.75</td>
</tr>
<tr>
<td>Troponin positive</td>
<td>1.76</td>
<td>0.76–4.07</td>
<td>0.19</td>
<td>1.68</td>
</tr>
<tr>
<td>Multivessel disease</td>
<td>0.90</td>
<td>0.40–2.05</td>
<td>0.80</td>
<td>1.02</td>
</tr>
<tr>
<td>Previous CABG</td>
<td>1.23</td>
<td>0.15–10.23</td>
<td>0.85</td>
<td>2.29</td>
</tr>
</tbody>
</table>

CABG indicates coronary artery bypass grafting; CI, confidence interval; FFR, fractional flow reserve; and MI, myocardial infarction.
from the passage of adenosine through the pulmonary circulation, inducing a short reflex peripheral vasoconstriction. After this reflex response, adenosine acts to decrease peripheral resistance with an associated fall in systemic BP.

Pressure, under conditions of stable hyperemia, is considered to be proportional to blood flow. However, our findings suggest that with central intravenous adenosine infusion, there is often an initial reflex rise in Pa, if FFR is measured prior to achieving stable hyperemia, the initial rise in Pa together with a large reduction in the Pd leads to the potential for overestimation of lesion severity. In contrast, under stable hyperemia, the FFR value is frequently higher, most often reflecting a fall in Pa and a rise in Pd, compared with peak measurements (Figure 5). It has been hypothesized that this increase in Pd in the face of continued falling Pa perfusion pressure reflects an autonomic vasoconstrictor mechanism of the coronary microcirculation. This has been termed paradoxical microcirculatory vasoconstriction. In such cases, the coronary microcirculation behaves like any other vascular bed—by vasoconstricting under conditions of low perfusion pressure to increase distal intracoronary pressure, and preserve flow.

Although adenosine is used to mimic exercise, recent studies have demonstrated that this pharmacological response differs from that during resistive nonpharmacological exercise. During exercise, both peripheral and microcirculatory resistance falls, and perfusion pressure to the coronary and systemic circulation is preserved by an increased cardiac output, most evident through a widening of pulse pressure. However, during adenosine infusion, Pa falls because of the reduction in peripheral resistance.

Over and above these differential responses between pharmacological and exercise vasodilatation, Siebes et al described the influence of pressure on FFR measurements in a theoretical model. These findings suggest that differential responses in pressure may be more widespread and unpredictable than frequently recognized. Our study supports the findings of this theoretical model and demonstrates that across the range of physiological stenoses routinely studied in assessment of intermediate stenoses, Pa, rather than reduction in coronary microcirculatory resistance, is on average responsible for the majority of the fall in Pd. This effect is most evident with larger falls in Pa and least with smaller reduction in Pa. Furthermore, when a reduction in Pa is large, the perceived reduction in Pd/Pa calculation is not due to a worsening of the stenosis, but due to lower Pa and Pd numbers. For example, if the pressure gradient is maintained constant, but Pa and Pd pressure lowered the pressure ratio (Pd/Pa) will get lower. This gives the artificial appearance that the stenosis has increased in physiological significance, but in fact this is not the case, and it is due to simple mathematics of ratio calculations. This suggests that where cardiac output cannot be increased to overcome the vasodilator-mediated reduction in peripheral pressure, FFR may be liable to be influenced by reduced left ventricular functional reserve.

We observed differences in the response of Pa and Pd when measured in different vessels within the same patients, suggesting that the systemic responses to intravenous adenosine are variable not only between individuals, but also between measurements within the same patient. Such differences are regularly observed with other drugs, which are usually expected to behave differentially within and between patients, frequently having different doses and different actions in different vascular beds in the same individual. It is, thus, likely and not at all surprising to see similar intra- and interpatient differential responses with adenosine. These findings may in part help explain the intrapatient variability of FFR classification.

**Impact of Changes in Systemic BP on FFR**

In this study, we found that changes in systemic BP caused by intravenous adenosine can lead to alterations in FFR lesion classification potentially affecting clinical management decisions. Specifically, we observed in 1 in 11 (9%) cases, a difference in classification when measurements were made at peak and stable hyperemic pressures using the widely acknowledged 0.8 FFR treatment threshold, and observed a difference in 1 in 19 (5.2%) cases using 0.75 FFR treatment threshold. Furthermore, mean peak and stable FFR values for the entire study group similarly crossed below and above the 0.8 FFR threshold. These findings highlight the importance of measuring FFR once stable hyperemic pressures are achieved as was the methodology followed in the FAME and DEFER studies. Otherwise, this could lead to significant alterations in FFR classification. Ideally, measurements should only be made when stable hyperemia is achieved after ≥60 seconds of stable intravenous adenosine infusion.

Using intravenous adenosine via a central venous line maintains a steady state, stabilizing hemodynamic conditions, and creates the optimal conditions for physiological lesion assessment. However, even when using the methodology used in the large clinical trials from which the outcome data were generated, differences between peak and stable measurement occurs. Although these differences may seem small whenever classification and therefore treatment strategy is changed between the initial (numerically lower) FFR measurement and that achieved at stable hyperemia, it will mean that unintentionally clinical decision making (to stent or defer therapy) will be made on a basis different from that used in the studies in which clinical outcome data have been generated. Importantly, all of these patients fall within the clinically important intermediate FFR 0.6 to 0.9 zone, and the impact of this difference in clinical decision making on clinical outcomes has not been rigorously assessed.

**Study Limitations**

This is the first study to our knowledge to demonstrate the impact of systemic hemodynamic change during measurement of FFR, and further studies are required for validation. This was a retrospective analysis of patients undergoing FFR measurements for assessment of intermediate coronary stenoses (mean stenosis severity, 49%; FFR, 0.83). It is, therefore, representative of a typical clinical workload where assessment of intermediate stenoses is in question, and typical clinical practice. Our study focused on hemodynamic changes attributable to intravenous adenosine infusion; however, some clinicians use bolus intracoronary adenosine. Measurement of FFR using intracoronary adenosine has been validated by large clinical outcome studies and may have less impact on systemic BP than intravenous adenosine. It is possible that differences in classification of FFR between intracoronary and intravenous adenosine may be attributable to the findings of
our study. Future studies, which include systematic measurement of both intravenous and intracoronary adenosine administration, would be needed to confirm this.

Conclusions
Intravenous adenosine significantly affects pressures in both systemic and coronary vascular beds. This can lead to significant differences in diagnostic classification when measurements are made between peak and stable FFR. To maximize the likelihood of obtaining the correct FFR classification, measurements should be made under conditions of stable hyperemia, as performed in the landmark FFR outcome studies.

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Disclosures
Dr Davies is a consultant for Volcano Corporation. The other authors report no conflicts.

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Hemodynamic Response to Intravenous Adenosine and Its Effect on Fractional Flow Reserve Assessment: Results of the Adenosine for the Functional Evaluation of Coronary Stenosis Severity (AFFECTS) Study


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